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MEAN DROPLET DIAMETER RESULTING FROM ATOMIZATION OF A TRANSVERSE LIQUID JET IN A SUPERSONIC AIR STREAM

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Nomenclature

α	size number
C_v	volume concentration
d	injector diameter
D	droplet diameter
D_{32}	volume to surface mean diameter
D_∞	specified upper limit diameter
E_o	incident planar wave irradiance
h	jet penetration height
J_1	Bessel function of first kind of ander unity
k	scattering coefficient
λ	wave length of incident beam
m	refractive index of the particles
$N_r(D)$	a known distribution function of droplet diameters
$\bar{q}$	ratio of dynamic pressure of jet $(1/2\zeta_{\infty 0} v_0^2)$ to dynamic pressure of freestream $(1/2\zeta_\infty v_\infty^2)$
τ	turbidity
$(\tau \ell)$	optical depth
Θ	scattering angle
$\bar{\Theta}$	reduced scattering angle = $\frac{\pi \Theta D_{32}}{\lambda}$
x	distance downstream of the center of injector
y	vertical distance from surface of the flat plate

I. INTRODUCTION

1.1 Background

Transverse injection of a liquid jet into a supersonic airstream is a problem of current importance in science and technology. Some aerospace applications of liquid jet injection are transpiration cooling of reentry bodies, thrust vector control of rockets and fuel injection for a supersonic combustion ramjet (SCRAMJET).

In high speed reentry, a very hot ionized layer of air surrounds the reentry body which is the cause of the "blackout" period. In order to provide local cooling in the region of a communication antenna to alleviate the blackout period, the possibility of injection of a liquid coolant into the ionized air layer surrounding the antenna has been considered. Therefore, accurate knowledge of jet spray parameters, liquid jet breakup, and the mean droplet diameter resulting from the decomposition of the liquid jet is essential in order to design an effective system.

Liquid injection into a supersonic airstream has similar applications both in thrust vector control and supersonic combustion ramjet. Although gaseous fuels have been considered for these applications, liquid fuels have the advantage of being denser, easier to handle and they also have lighter control systems. For cost, safety and availability reasons, it is likely that kerosene-type liquid fuels will be employed as the energy course for the supersonic

combustion ramjet. The efficiency of the supersonic combustor of a scramjet plays an essential role in the overall performance of the scramjet vehicle. The combustion processes are controlled by mixing of the fuel and air and by the chemical heat release. This process not only must be efficient at the design point, it must also be efficient and adequate in off-design regimes. The demands on the efficiency and performance of the combustor are directly linked to the injector, which places restrictions and demands on the injector/jet parameters. Again, such matters as liquid jet penetration, jet break-up and atomization must be clearly understood to produce an efficient design without excessive, expensive trial-and-error testing. A brief consideration of the operation of thrust vector control systems using jet injection will also lead to the same type of basic knowledge requirements as local cooling and scramjets.

By injecting a liquid jet into a supersonic airstream, one creates a boundary layer separation zone upstream of the injector. This is produced by an interaction of the boundary layer and the shock caused by the transverse jet (see Fig. 1). This separation zone plays an important role in combustion since the rate of heat transfer is often the highest in parts of a separation zone. It might also provide the most favorable conditions for auto-ignition of the fuel. The interaction shock system itself associated with each injector has two effects. First, the shock reduces the total pressure of the free airstream and therefore tends to reduce the overall performance.

Second, due to the shock, the static pressure, and temperature of free airstream will rise. Therefore, a better condition to support possible ignition and chemical reactions is created out in the main stream.

The study of droplet sizes produced as a result of jet break-up is important for all potential practical applications. The size of the liquid particles resulting from transverse injection of liquids into a supersonic airstream is clearly determined by the injector geometry and characteristics and the flow parameters. By reducing droplet size, one can reduce the residence time, evaporation time and mixing time, thus reducing the required overall length of the combustion chamber. This in turn results in a shorter and lighter engine.

Sherman and Schetz, Ref. (1), were among the first to study the detailed structure of a transverse liquid jet and a parallel liquid sheet in a supersonic flow by using the photomicrograph technique. They concluded that the jet break-up is brought about by cross-jet fracture at a wave trough (See the close-up photo in Fig. 2). This process is cyclic.

Kush and Schetz, Ref. (2), performed extensive experimental work to study the effects of free stream Mach number, free stream total pressure, injector diameter, injector shape, injectant flow rate and injectant properties on jet penetration and structure. They also reported data on wave length, amplitudes and wave speed of the

disturbances on the jet surface that lead to break-up of the jet. It was also noted that the injector geometry has a significant effect on jet penetration and the liquid surface layer near the jet, which is caused by the interaction of the three-dimensional shock system with the boundary layer.

Joshi, Jakubowski, Schetz, Ref. (3), also investigated the effects of injector geometry on penetration and structure of the liquid jet. They found a relation between penetration and jet/free stream dynamic pressure ratio. They also found the dependence of penetration on injector geometry, characterized by the ratio of the frontal dimension to the stream wise dimension. It was observed that for a given mass flow rate of injectant, a rectangular injector has the highest penetration and spread.

Studies by Schetz, McVey, Padhye and Munteanue, Ref. (4), also investigated the behavior of liquid jets injected normal to a high speed airstream. Although this report dealt with normal injection of liquids into a high transonic speed airstream, it comes closer to the present work than any of the other investigations in the respect that droplet size and distributions were investigated. Ref. (4) employed the photomicrograph technique for the droplet size investigation, and concluded that:

a) the mean droplet size was of the order of 10^{-2} inch
b) for a given injector and airstream conditions, the mass flow rate of the injectant did not affect droplet size

c) an increase in orifice diameter of the injector increased the droplet diameter

d) an increase in M decreased mean droplet diameter size

e) injector geometry had a significant effect on mean droplet diameter.

Weiss and Worshom, Ref. (5), studied the atomization of molten Acrawax-C jet in a high-velocity airstream and obtained the diameter of the frozen jet particles. They concluded that the particles were almost uniformly spherical. This finding supports an assumption used in the present investigation. Ref. (5) also studied the effects of airstream density, relative velocity, liquid viscosity, mass injection rate and injector diameter on droplet diameter. It was concluded that relative velocity between airstream and the liquid jet is of prime importance and that physical properties do affect spray fineness, but their net influence is less critical. Also, they correlated the results empirically by a dimensionless equation.

Adelberg, Ref. (6), theoretically estimated the mean droplet diameter generated by a liquid jet penetrating a gaseous environment. He divides the region of interest into four separate regions according to the relative dynamic pressure and treats the two regions having the higher dynamic pressure. He states that the mechanism of ligament formation and shedding appears to be a good model for droplet formation in the case of high relative velocity between liquid jet and the surrounding gas stream. The analytical results are compared with

the experimental results obtained by Weiss and Worsham and it is found that the analysis is in good agreement with the experimental results. He also compares his results with Mayer's analysis, Ref. (7), and finds that his predicted droplet diameter is different from that of Mayer. Some of Adelberg's assumptions have, however, been criticized.

Forde, Molder, and Szpiro, Ref. (8), constructed a simple theoretical model based on Newtonian flow concepts, for the prediction of the injectant path, and hence the penetration distance for secondary liquid injection into a supersonic stream. The experiments showed that it is possible to achieve significant penetration distance by injecting liquid from a wall orifice into a Mach 3 supersonic airstream. They also concluded that:

a) the model predicted the penetration height with reasonable accuracy,

b) the maximum penetration is dependent on injectant total pressure, the angle of injection and injector diameter,

c) upstream injection produced the longest penetration height whereas a small angle downstream gave a slightly greater penetration than the normal injection.

Reichenbach and Horn, Ref. (9), experimentally investigated the effect of liquid properties on secondary injection from a single small-diameter nozzle in a supersonic stream. By injecting superheated water and acetone, they investigated the effect of vapor

pressure on penetration. Penetration height was correlated with injector pressure ratio for super-heated liquid injection; these data were compared with room temperature results. They concluded that vapor pressure break-up outside of the spray nozzle had little effect on penetration. The effects of liquid viscosity and surface tension were also studied, and they reported that neither property effected the penetration height for flow in the acceleration wave break-up regime.

Gooderum and Bushnell, Ref. (10), conducted a study of atomization, droplet size and penetration measurement for cross stream water injection at high altitude reentry conditions. The work employed the scattered light technique in measuring the mean droplet diameter of the spray particles. Data was obtained in both a static environment and in conventional aerodynamic facilities at Mach number of 4.5 and 8. It was concluded that the mean drop size for vapor pressure breakup in the absence of external flow is directly proportional to orifice diameter, and is an inverse function of the absolute temperature of injectant. They also reported that the droplet size resulting from injection into Mach 8 cyanogen-oxygen tunnel were independent of injectant (water) velocity.

Horn and Reichenbach, Ref. (11), further investigated the penetration and width spread of a liquid jet in supersonic flow. They presented information on lateral spread of a jet and stated that the lateral spreading width has a weak dependence on injector

pressure ratio. Ref. (11) also studied the effect of Mach number on the lateral spreading width of a liquid jet and concluded that lateral width of a liquid jet spray has a weak Mach number dependence.

In summary, it can be concluded that while several studies of transverse liquid jet injection into supersonic flow have been presented, there is little information available pertaining to droplet sizes in the spray.

1.2 Aim of the Present Work

The study of liquid jet characteristics is not complete if the droplet size and the distribution of the droplet sizes are not known. This information will result in a better understanding of how the jet is atomized, at what location the decomposition is complete and also the length required for complete decomposition in the airstream.

Although all of the work mentioned above has contributed to the background of the present work, the prime motivations arose from the hardships encountered in obtaining the droplet size diameter in the work of Schetz, McVey, Padhye, and Munteanu, Ref. (4). The use of high-speed photomicrography to examine the droplet size seems very appropriate. High speed photomicrography may, in principle, be the best and the most accurate technique which can be employed to obtain particle size, however, there are many practical diffuculties associated with this technique. Several of these are: 1) the difficulties related to sufficient resolution, 2) the very small depth of focus required, 3) the small number of particles

usually present within the focal plane and the question of whether these particles constitute a representative statistical sample, 4) the differentiation between the film grain and droplet image, 5) the problem of deciding between single droplets or clumps, and 6) perhaps most important, the very tedious process of counting and measuring the droplet sizes one by one. The excessive labor associated with droplet size determination by high-speed photomicrography and the awkward procedure are the major drawbacks. One also has to consider the cost effectiveness of a proposed experimental technique. If the test technique itself is simple and cheap, but the data reduction is neither, no advantage results.

In view of these reasons, other techniques, although perhaps not quite as accurate or precise as photomicrography, have been sought to determine the sizes from liquid jet atomization. Such a technique must be reasonably accurate, readily available, adaptable and easily manipulated. One technique that determines particle size in liquid droplet clouds with potentially good experimental accuracy is based on the light scattering properties of particles. This technique is known as the Diffractively Scattered Light Method.

The aim of our work here was to study the utility of this technique to measure droplet size diameter in the spray that results from transverse liquid injection in a high-density, supersonic airstream and to determine the accuracy of the method. Since such experiments are normally performed in a closed test section wind

tunnel, the problems, if any, that result from the necessarily thick windows were also of prime interest. To the best of our knowledge, this study is the first published dealing with an attempt to obtain mean droplet diameter at high density, supersonic conditions. Therefore, there was no other work available for direct comparison of the results.

II. THEORETICAL CONSIDERATION

2.1 Theoretical Consideration for the Optical System

The investigation of the light scattering technique was first conducted by Chin, Sliepeevich, and Tribus, Ref. (12), using a theory by Gumprecht and Sliepeevich, Ref. (13), which describes the scattering properties of a polydispersion. This theory requires very low droplet concentrations to constitute a small optical depth. It further requires that both particle size and refractive index fall within given intervals. The formation of a theory for the scattering properties in the more general case of particles of arbitrary size and arbitrary refractive index occuring in a polydispersion of finite optical depth has been discussed by Dobbins, Crocco, and Glassman, Ref. (14). Much of what follows in this section comes from their work. Eqn. (1) gives the radiant intensity, $I(\Theta)$ scattered at a small angle, Θ measured from the forward direction (centerline).

$$\frac{I(\Theta)}{E_0} = \frac{D^2}{16}\left\{\alpha^2\left[\frac{2J_1(\alpha\Theta)}{(\alpha\Theta)}\right]^2 + \left[\frac{4M^2}{(m^2-1)^2(m+1)}\right]^2 + 1\right\} \quad (1)$$

This equation is derived from the scattering of light by a single dielectric spherical particle. The particle has a size number $\alpha = \frac{\pi D}{\lambda}$ where D is the diameter of the particle and λ is the wave length of the incident light beam, E_0 is the incident planar wave irradiance, J_1, is the Bessel function of the first kind of order

unity and m is the refractive index of the particles. The three terms in the bracket of Eqn. (1) represent the Fraunhofer diffraction, the optical scattering due to refraction of a centrally transmitted ray and the optical scattering due to a grazingly incident ray, respectively.

Five conditions must be met to assure the validity of Eqn. (1):

1) The incident radiation must be planar.

2) The forward angle, Θ, must be small.

3) The particle size number $\alpha = \frac{\pi D}{\lambda}$ and phase shift $[2\alpha(m - 1)]$ must be long.

4) The distance between the particles and the observer must be large compared to $\frac{D^2}{\lambda}$.

5) The particles must be non-absorbing (of light).

If a polydispersion of particles is present, the integrated intensity from all particles is found by summing over all diameters. A distribution function $N_r(D)$ is defined in such a way that the integral of $N_r(D)$ over a given diameter interval represents the probability of occurrence of particles within the specified interval. This function determines the relative frequency of occurrence of particles of a given diameter, D. The expression for the intensity of scattering due to a polydispersion is normalized by dividing by the intensity of diffractively scattered light in the forward direction ($\Theta = 0$, centerline). This procedure allows one to discard the second and the third terms of Eqn. (1), since they are small.

The normalized, integrated intensity of forward scattered light $I(\Theta)$ due to a polydispersion of large particles is given as:

$$I(\theta) = \frac{\int_0^{D_\infty} [2J_{(\alpha\Theta)}]^2 N_r(\phi) D^4 Dd}{\int_0^{D_\infty} [N_r(D) D^4] dD} \qquad (2)$$

Eqn. (2) requires that the attenuation of the incident beam be slight, so that all particles are illuminated equally.

By employing the definition of turbidity (τ),

$$\tau \equiv \frac{\pi}{4} C_n \int_0^{D_\infty} K(D,m) N_r(D) D^2 dD \qquad (3)$$

the mean scattering coefficient, k, volume to surface mean diameter, D_{32}, and the volume concentration, C_v, the transmission law can be expressed as

$$E/E_o = \exp(-\tau\ell) = \exp[-\frac{3}{2}(kC_v \frac{\ell}{D_{32}})] \qquad (4)$$

For a detailed explanation, see Ref. (14). The restriction on Eqn. (2) that the particles must be illuminated equally is fulfilled when the optical depth ($\tau\ell$) is small compared to unity. However, when the effect of finite optical depth was studied, it was found that the influence of multiple scattering on the illumination profile is weak. It was recommended that the optical depth be maintained below (1.5) in order to assure the absence of an adverse distribution of illumination profile.

Eqn. (2) represents a relationship between the angular distribution of scattered light in terms of the particle size distribution. The important question was whether a knowledge of the angular distribution of scattered light intensity, I(Θ), determined experimentally could be used to supply some information about the particle size distribution. This question was resolved by examining the illumination profile, I(Θ), for various distribution functions representative of those of interest. A problem arises from the fact that one does not know what distribution function is a good respresentative of the particle sizes being investigated. Mugele and Evans, Ref. (15), have shown that choosing the parameters in these distribution functions in such a manner as to fit a size histogram closely can predict a completely inaccurate volume fraction curve or give incorrect values of the mean diameters. These shortcomings were resolved in Ref. (13) by use of Upper Limit Distribution Function (ULDF) proposed by Mugele and Evans. The ULDF has the property that no particles exist at sizes larger than a specified D_∞. Again however, knowing the upper limit of particle size in many cases is impossible. Roberts and Webb, Ref. (16), studied the accuracy of the Diffractively Scattered Light Method in measuring particle size by using many different distribution functions. They concluded that the value of a mean diameter, D_{32}, may be determined from the intensity of diffractively scattered light from a

polydispersion of spherical particles to a good degree of accuracy for an extremely wide range of distributions and without the knowledge of general distribution type. They plotted the mean theoretical illumination profile for all distributions investigated, Fig. (3). This profile can be regarded as a universal illumination profile and has been utilized in the current study in obtaining mean droplet diameter of particles. Of course, one is now limited to determining only the value of a mean droplet size and not the distribution of sizes.

III. EXPERIMENTAL INVESTIGATION

3.1 Test Facility

The current study was conducted in the VPI&SU 9 inch x 9 inch supersonic wind tunnel. This tunnel is a blow-down type with interchangeable test sections capable of producing free stream Mach numbers of 0.4 to 4.0. In the current investigation, the test section was chosen to produce a free stream Mach number of 3.0. A series of calibration investigations have confirmed the uniformity of the flow in the test section. Throughout the experimental work, the stagnation temperature of the free steam was that of the [illegible] air (roughly 75°F). The stagnation pressure was controlled [illegible] a ±3%. Large thick glass windows normally cover the sides of the [illegible] section. These windows were found to be of insufficient quality, and they were replaced for the present work.

3.2 Flat Plate Model

The liquid jet injection was carried out through a flat-plate model with a sharp leading edge. The flat plate had dimensions of 4 in. x 5 in. with the orifice of the injector located 2 in. downstream of the leading edge, Fig. (4). The plate was mounted on a sting and was located at the center of the test section. The circular injectors were tested, one with an orifice diameter of 0.0285 in. and the other with an orifice diameter of 0.059 in. The discharge coefficient of both injectors was assumed to be unity. The

injectors were made of brass and were interchangeable from beneath the flat plate. The top surface of the injectors were flush with the surface of the flat plate. Each injector had a 1/16 in. straight run and a smooth conical entry passage. A 1.0 in. inside diameter plenum chamber was fitted to the flat plate underneath the injector and sealed with a rubber O-ring. The large size of the plenum chamber compared to the size of the injector reduced the disturbances in the injectant. Liquid injectant was supplied to the plenum chamber by a 3/8 in. O.D. copper tubing.

There were two reasons that injection through a flat plate was chosen over the injection through the test section walls:

1) the great reduction of boundary layer thickness
2) the advantage of having a degree of freedom to rotate the flat plate vertically in the test section to allow viewing the jet from "above".

3.3 Injection System

A schematic diagram of the injection apparatus is shown in Fig. (6). A large stainless steel tank was utilized as the injectant reservoir which was pressurized by nitrogen gas. The size of the tank played an important role in maintaining a constant injection pressure in the plenum chamber during each run because the volume of the injectant injected during each run was small compared to the total volume of the injectant stored in the tank. The tank pressure was regulated to help attain the desired mass flow rates through the

injector. The pressurized injectant passed through a solenoid valve which was remotely operated to start and stop the flow. The solenoid valve was then followed by a needle valve which regulated the mass flow rate of the injectant. The needle valve was connected in series to a manual valve for a safety factor, so that if the solenoid valve should fail the flow of injectant could be stopped. This valve was followed by a filter which had the capability of removing foreign material larger than 140 microns from the injectant. The filter led to a turbine-type flow meter to measure the mass flow rate of the injectant. Copper tubing of 1/2 in. O.D. was used for this series of connections. After the flow meter, the diameter of tubing was reduced to 3/8 in. O.D. in order to make the connection with model plenum chamber possible.

Throughout this experiment, water was used as the injectant for safety and convenience. What earlier work does exist indicates that fluid properties are not of first order importance; obviously, this point needs further study and verification.

3.4 Flow Instrumentation

The pressure inside the plenum chamber was measured by a transducer to make sure there were no pressure fluctuations in this chamber during each run. The stagnation pressure and temperature of the free airstream were measured in the settling chamber of the supersonic tunnel. All the outputs of the transducers and the

thermocouple were recorded on strip chart recorders. The flow meter was calibrated for water and alcohol, and its output was directly read from a digital voltmeter and recorded during each run.

List of Instruments and Their Specifications

1. Free stream pressure transducer: Frederic Flader Engineering Physics division

   Range of 0-100 psi (no model number)

2. Model plenum chamber pressure transducer: Statham model 4-326

   Range of 0-1000 psi

3. Solenoid valve: ASCO Model 8266C1 400 psi max

4. Filter: NUPRO Model B6TF2-60 140 microns

5. Flow meter: Pottermeter Model 1/2 - 468 THM - 60

   9 GPM maximum flow.

6. Recorders: Hewlett Packard Model 7100B

3.5 Optical Arrangement

A schematic diagram of the final optical set up is shown in Fig. (6). For ease of operation, all of the optical equipment with the exception of the windows, were mounted on a home-made optical bench with two degrees of freedom (vertical, horizontal). A Helium-Neon Laser was used as the light source. A spatial filter located directly in front of the light source produced a larger diameter and more uniform light beam than that of the laser alone. Two circular glasses 2 in. in diameter and 1/2 in. thickness were

used as windows, one on each side of the test section. A plano-convex lens, 2 in. in diameter with a focal length of 19.7 in., was used as the condensing lens. This lens focused the unscattered light beam on an aperture of 0.006 in. diameter located directly in front of the photomultiplier tube. The photomultiplier assembly which consisted of a 3 in. diameter pipe 8 in. in length contained the photomultiplier tube, its circuitry and the 0.006 in. aperture. The aperture plate was located 1/4 in. in front of the photomultiplier tube, and it completely sealed the tube inside the photomultiplier assembly.

The photomultiplier assembly was mounted on a traverse mechanism which allowed a smooth and constant speed scanning of the scattered light illumination profile intensity. We require the illumination profile intensity versus the scattered angle, Θ. The travel distance of the photomultiplier tube was recorded by employing a ten turn potentiometer.

Three separate D.C. voltage sources were used with the optical system - one to supply power to the ten turn potentiometer, one to energize the traverse mechanism and one to supply voltage to the photomiltiplier tube. The output of the photomultiplier tube and the ten turn potentiometer were both recorded on one recorder.

The Diffractively Scattered Light Method for obtaining mean droplet diameter is new and underdeveloped for some experimental

conditions. Therefore, for the benefit of the future experimentalists it was thought essential to report here our experiences with this technique. The technique appeared to have been simple, but as with all optical investigations, there were many hidden points that caused problems in obtaining useful results. The choice of each component of the optical set up was critical to the outcome of the experiment. Each component was chosen based on a year's gathering of data and experience. The final optical set up was the best suited for our high-density, supersonic air experimental condition.

In view of our initial lack of experience and also the lack of comprehensive previous reported research in this area, the first optical set-up used was an almost exact duplicate of the system employed by Gooderum and Bushnell, Ref. (10). Their set-up served as the starting point and many improvements were required to be made to make a workable system for the current experimental conditions. The optical set-up used by Gooderum and Bushnell consisted of:

1) Mercury arc lamp (BH-6 air cooled) as the light source
2) collimating lens
3) interference filter
4) condensing lens
5) slit
6) collimating lens

7) windows

8) condensing lens

9) rotating flat mirror

10) photomultiplier tube

The hardest and the most important part of developing the Diffractively Scattered Light Method was to obtain a clean, parallel and uniform monochromatic light beam to pass through the test section. Experience showed that the fewer the number of optical components, the easier this task was to achieve. Alteration to the basic Gooderum and Bushnell set-up was made to improve the light beam and to reduce the number of optical items. The final optical arrangement and the reasoning behind each improvement are described below.

3.5.1 Light Source

The change from a Mercury arc lamp to a Helium-Neon laser as the light source had many benefits.

a) The laser produced a more powerful light beam which allowed the use of a pin-hole as compared to the slit which was necessary for the Mercury lamp.

b) The laser itself produced a nearly parallel beam.

c) The laser produced a monochromatic light beam (λ = 6380 A°) which eliminated the need for an interference filter. Hence, there was no absorption and no additional

scattering due to the interference filter.

d) The light beam alignment was much easier with the laser.

3.5.2 The Collimating Apparatus

Although the laser produced a parallel light beam with good intensity, it still did not meet the severe requirements that the technique imposes on the light beam. The light beam passing through the test section had to be parallel, free of noise and uniform. Also, the size of the beam was important and the ability of controlling the beam diameter without introducing added refraction and noise to the beam was essential in the experiment. Through usage of a Spatial Filter all of these requirements were met. The Spatial Filter consisted of three parts:

1) the condensing lens
2) the pinhole
3) the collimating lens.

The condensing lenses were microscope objective of 5X, 10X, 20X, 25X, each of which had different focal lengths. Each one of these condensing lenses produced a different diameter light beam. In this experiment 25X objective was used which produced a final beam diameter of 5mm. The condensing lens focussed the light from the laser on a pinhole. The right combination of pinhole diameter and condensing lens produced a very fine uniform ring (Fraunhofer) free light beam. The pinhole also served to meet the theoretical

requirement of having a point source. The collimating lens of the spatial filter produced the final parallel light beam. The advantage of spatial filtering was that it provided fine adjustment for light beam alignment and also eliminated the need of a diaphragm for controlling the beam diameter.

3.5.3 Windows

The first important medium that the light beam passes through before passing through the spray is the glass wind tunnel window. The light beam has to remain essentially unchanged while passing through these glass windows, so that the only scattering is produced by the jet particles in the test section. Any additional scattering from the windows reduces the accuracy of the technique. The regular wind tunnel windows created problems in obtaining useful scattering of the light beam. Special glass plates were therefore used as the windows. The quality of the new glass windows were checked once by obtaining the scattering of the light beam due to optical equipment without the windows and then comparing the results with zero scattering obtained while the windows were in place. The glass windows in the present experimental set-up did not produce any additional scattering. The thickness of the glass windows dictates its absorption. The light absorption due to the windows had to be very slight. This phenomenon was also checked and was proven to be satisfactory.

3.5.4 Condensing Lens

The task of the condensing lens is to focus the unscattered light beam on the aperture in front of the photomultiplier tube. Hence, this lens had to have a precise focal point, and it also had to be scatter free. The focal length of the lens was important, since it was used in data reduction. Obviously, no additional scattering of the light should result from this lens. Experience showed that the condensing lens should be mounted with an angle of greater than ninety degrees with respect to the light beam. This procedure eliminates the reflection of the light beam from the lens surfaces which travel back into the test section. Therefore, the scattering intensity due to optical set-up (zero scattering) was reduced.

3.5.5 Scanning of the Scattered Light Illumination Profile

The heart of the Diffractively Scattered Light Method is the system to measure the intensity of the scattered light vs. the angle of scattering. In order to accomplish this task, one has to scan the intensity of the scattered light illumination profile with a detection device. There are two different methods of scanning the intensity of the light profile:

1) have the detection device stationary and move the illumination profile
2) have the illumination profile stationary and move

the detection device.

In order to move the illumination profile in front of the detection device, many complicated mechanisms were required. Also, additional optical equipment such as a rotating mirror were necessary. The additional optical equipment produced additional light scattering. Therefore, this method of scanning was not acceptable, and it was rejected.

The simplest and the most accurate system was to mount the photomultiplier tube on a traverse mechanism and to leave the light beam stationary. This system allowed an accurate scanning of the scattered light profile and provided freedom over the rate of scan and the total angle scanned. It also protected the photomultiplier tube from the center-line, unscattered, high-intensity light beam. The most significant aspect of the traverse mechanism was that it did not require any additional optical equipment to be placed in the light path.

3.5.6 Photomultiplier Tube

An RCA Type C7164R was chosen as the light intensity detection device. Type C7164R was specially designed for Helium-Neon laser applications. It had a fast response time, and a very low dark current. However, if it were exposed to flourescent light, the dark current would have increased by orders of magnitude and would have lasted for several days. To protect the photomultiplier tube from

flourescent light and all other unwanted lights it was housed in a circular pipe of 3 in. diameter and length of 8 in. This circular pipe at one end was covered with the aperture plate with the 0.006 in. diameter hole at the center as the aperture, and at the other end it was completely sealed. The optical set-up in the current study proved to produce low levels of zero scattering and also used fewer components when compared to other experimental set-ups.

3.5.7 List of Optical Equipment

1. Laser: Spectra physics Model 120 Helium-Neon 5M Watts
2. Spatial Filter: JODON Model BET-25 beam expanding laser collimater
   a) Lpsf-100 Spatial filter consisting of 5X, 10X, 20X, 25X, microscope objective and 15, 20, 25, 50, 100 micron pinhole
   b) CL-25 27mm diffraction limited telescopic lens
3. Windows: ORIEL Model A-43-564-80 precision flat windows (2) of Schlieren-free fused silica
   2 in. diameter
   0.5 in. thickness
   1 sec. parallelism with surface profile for

research grade, optical polish for low light scatter.

4. Photomultiplier tube: RCA Model C7164R
5. DC power supply: ORTACE Model 456H)0-3k) DC voltage (supplier for photomultiplier tube only)
6. Recorders: Hewlett Packard Model 7100B

IV. CALIBRATION OF THE DIFFRACTIVELY SCATTERED LIGHT METHOD

The accuracy of the Diffractively Scattered Light Method in obtaining the mean diameter of particles was investigated in two separate cases. These two cases were selected to be representative of our actual experimental conditions. First, the mean droplet diameter of water particles produced by an atomizer was measured by both the Diffractively Scattered Light Method and the direct photomicrographic technique. Second, the mean diameter of known sized glass beads were measured by the Diffractively Scattered Light Method.

In measuring the particle diameter of the atomizer spray, the optical set-up was the exact set-up used in the supersonic injection investigations, however the experimental conditions were different. The atomizer discharged the water particles into still air as compared to the injection into supersonic airstream for the main test program. The particle sizes produced by the atomizer were also measured by the photomicrographic method, and the results were compared to the mean droplet diameter obtained by light scattering technique. The results were in good agreement. The photomicrographic technique revealed an average droplet diameter of 24.6 microns, and the Diffractively Scattered Light Method showed a mean droplet diameter of 29 microns. This amounts to an error of 5.5% which was within our experimental expectations.

Using the same optical set-up, the mean diameter of known sized glass beads were measured. The bead diameter size range was from 48-53 microns. The different diameter sizes were necessary to assure polydispersion scattering of the light as required by the theory. The Diffractively Scattered Light Method measured a mean diameter of 48 microns, which is again within 5% accuracy of the true average diameter.

Although, the calibration tests were conducted in still air, it is believed that these results demonstrate the accuracy of the Diffractively Scattered Light Method in obtaining the mean droplet diameter of particles under conditions representative of those to be encountered in our experiments in a supersonic air stream.

V

5.1 Experimental Procedure

The fluid was injected over a wide range of jet/free-stream dynamic pressure ratio, and the mean droplet size of the particles in the plume were measured at several stations, Fig. (7), and tables (A.1-A.8). Two types of tests were conducted.

First, in each case a separate run without injection was run to determine the background scattering of the light due to optical equipment and supersonic flow. Theoretically, there should be no scattering of light by the optical equipment and the air flow. Null-condition scattering provided information about the light beam and flow conditions. Based on the experience gathered throughout this investigation, some techniques were developed to insure the quality of the light beam. The light beam has to be free of noise, diffraction, and Fraunhofer ring pattern. The most reliable technique was as follows. The unscattered light was focused on the aperture. The location of the aperture was recorded as the center line (CL) where $\Theta=0$. Theoretically, one should have no scattering profile on the aperture plate. However, there was a slight diffraction due to optical equipment and small random particles in supersonic air flow which resulted in a very low intensity scattering profile on the aperture plate. The quality of the light was judged by how close the aperture could come to the center line

location (Θ=0) without a high output from the photomultiplier tube. In the case of this study the minimum distance of aperture from center line was 0.020 in., corresponding to a scattering angle of Θ = .001016 rad. The offset distance of the aperture was important since, through extrapolation, one had to find the intensity of the diffractively scattered light $(I)_{CL}$ in the forward direction (Θ=0) Fig. (9). Through the same procedure, the intensity of the diffractively scattered light $(I)_{CL}$ in the forward direction (Θ=0) for the case with injection was established Fig. (10). The difference between the scattered light intensity due to liquid particles and the zero scattering intensity was normalized by dividing by $(I-I_o)_{CL}$. Once the quality of the light was established to be satisfactory, the zero scattering of optical equipment plus supersonic flow was investigated. Investigation showed that there was not a significant difference in the zero scattering with and without the supersonic air flow. This also provided a good test for establishing the condition of the supersonic air. It was noted that an "unstarted" tunnel flow produced scattering of the light beam, presumably due to condensed water vapor.

Second, injection runs were conducted to measure the intensity of the scattered light illumination profile due to atomization of the jet in the supersonic flow. During each run, the stagnation pressure and temperature of the free airstream, the mass flow rate

of the injectant, the pressure inside the model plenum chamber, the barometric pressure and the output from the photomultiplier tube and the ten turn potentiometer were recorded on stripchart recorders.

5.2 Test Procedure

1) The laser and the photomultiplier tube were energized and were allowed to reach a steady state.
2) The tunnel room was made completely dark.
3) The uniformity of the light beam produced by the spatial filter was checked.
4) The tunnel, the injector (when used) and the recorders were switched on and, after the supersonic flow had started, the photomultiplier tube was used to scan the illumination profile intensity of the scattered light.
5) If there was injection, the injector was turned off after completion of the scan.
6) The tunnel was shut down.
7) The recorders were turned off.

The duration of each run was between 7-10 seconds, and the time necessary for the photomultiplier tube to scan the illumination profile was 5 seconds.

The location of the light beam with respect to penetration height was then changed, and the test procedure was repeated. In

most of the tests the light beam was 6 centimeters downstream of the injector orifice, see Fig. (7).

VI. RESULTS AND DISCUSSION

6.1 Results

The jet/free-stream dynamic pressure ratios were calculated based on the recorded data for the stagnation pressure and the temperature of the airstream, the mass flow rate of the injectant and the diameter of the injector. Other recorded data such as the pressure inside the plenum chamber served to document test conditions, uniformity and the repeatibility of the experiment.

The intensity of the scattered light illumination profile was measured and normalized. The mean theoretical illumination profile curve, Fig. (2) was utilized to find the values of the reduced angle ($\overline{\Theta} = \frac{\pi \Theta D_{32}}{\lambda}$). From the value of $\overline{\Theta}$, the mean droplet diameters were calculated. Many points were examined on the mean theoretical illumination profile curve for each run. The reported mean droplet diameter are the average value in each case.

All measurements were taken at a plane normal to the free stream at a downstream distance of X/d = 82.88 for injection with a diameter of 0.059 in. and x/d = 48.34 and 82.88 for injection with a diameter of 0.0285 in. Also, tests were made to determine the mean droplet diameter variation across the jet with respect to penetration height.

The results are tabulated in Tables A-1 through A-8 and a short discussion of the tables follows. Each table contains five columns,

one each for x/d, h/d, y/d, $\bar{q}$ and D_{32}. The h/d entries are calculated values of the penetration height at the relevant station and conditions using the correlation formula of Ref. (3). The penetration is taken as the time-averaged top of the liquid plume. This information is provided, so that the reader may judge the relative location of the measurement point within the jet plume.

In able A-1 the effect of jet/free-stream dynamic pressure ratios, $\bar{q}$, on the mean droplet diameter is shown. The location of the light beam passing through the jet was fixed at a downstream distance of $x/d = 48.35$, and a height of $y/d = 15.35$ for all the measurements. The results show that there was on inverse relation between mean droplet diameter and the ratio of dynamic pressures.

Table A-2 shows the effect of $\bar{q}$ on the mean droplet diameter. The measurements in this table in contrast with table A-1 were taken at the fixed station $x/d = 82.88$ and $y/d = 13.15$. This table shows that the mean droplet diameter decreased with an increase in $\bar{q}$. Also, the comparison of tables A-1 and A-2 reveals that the mean droplet diameter was smaller at stations farther donwstream from the injector orifice.

The mean droplet diameter variation across the jet penetration height at a fixed downstream distance of $x/d = 82.88$ and $\bar{q} = 4.61$ is given in table A-3. The results show that the mean droplet diameter decreased near the plume edge.

The data of Table A-6 were obtained with a new value of $\overline{q} = 18.05$, as opposed to Table A-3 where $\overline{q} = 4.61$. The pattern of data behavior in Table A-4 and A-3 were similar, i.e., the mean droplet diameter decreased near the plume edge.

In Table A-5 the mean droplet diameter at different penetration zones of the liquid jet produced by an injector of diameter .059 in. was investigated. In this study $x/d = 82.88$, $3.17 \leq y/d \leq 10.59$ and $\overline{q} = 2.40$. Here, the mean droplet diameter also decreased as the plume edge was approached. The comparison of these results to those of Tables A-3 and A-4 reveals that, first the mean droplet diameter was larger and second, the droplet diameter decrease did not follow a simple pattern.

Tables A-6, A-7, A-8 contain the results of the mean droplet diameter distribution across the jet penetration. In all of the investigations $x/d = 82.88$, $\overline{q} = 3.31$, 8.23, and 12.54 respectively. In each case, the light beam location y/d with respect to penetration height was changed. The results from each table show that the mean droplet diameter was smallest near the plume edge.

The results may be summarized as follows:

I) The mean droplet diameter was of the order of 10 microns.

II) Holding all the test conditions constant, an increase in $\overline{q}$ decreased the mean droplet diameter. For example, for

the injector with diameter of 0.0285 in. at $y/d = 18$ and $\bar{q}$ of 6.56, a mean droplet diameter of 20 microns were measured. The same injector with the same experimental conditions but with injection at $\bar{q} = 27.7$ produced droplets with mean diameter of 17 microns.

III) Since $\bar{q}$ and mass flow rate have a direct relation, one can deduce that an increase in mass flow rate decreases the mean droplet diameter.

IV) There was a direct relation between the particle size and the diameter of injector. For example, the 0.0285 in. diameter injector produced 11 micron particles at $y/d = 13.15$ and $\bar{q} = 8.28$. Injection through the 0.059 in. diameter injector yielded droplets of 28 microns at identical experimental conditions.

V) There was no simple pattern to the variation of droplet size across the jet plume.

6.2 Discussion

Mean droplet diameter of spray particles resulting from atomization of a transverse liquid jet in a supersonic flow was investigated using the Diffractively Scattered Light Method. Although the range of the test cases was limited, the results helped to determine the utility of this technique in measuring the mean droplet diameter under higher density, supersonic flow conditions.

This technique confirmed that the mean droplet diameter has an inverse relation with jet/free-stream dynamic pressure ratio. There was also a direct relation between the droplet diameter and the injector diameter. Throughout the range of dynamic pressure ratios, the larger diameter injector consistently produced larger diameter droplets than the smaller diameter injector. The distribution of droplet diameter across the jet with respect to penetration height did not have a simple variation. This contradicts our expectations prior to the investigation, however, the mean droplet diameter at each station decreased as the dynamic pressure ratio increases. The mean droplet diameter was the smallest near the plume edge. This phenomenon seems to be logical since the decomposition of a jet starts at the surface.

The test cases were limited in number, but the repeatability, and apparently, the accuracy of the experiment were good. Casual comparison of data points against each other at apparently identical conditions may tend to mislead one into condluding that there are inconsistencies in the data. The reason for such apparent small inconsistencies arises from the fact that each data point was taken at an approximate jet location. The jet profile and penetration are very sensitive to dynamic pressure ratio of the jet/free-stream, and experimentally, it was difficult to repeat exactly all the conditions that lead to $\overline{q}$ for a given test. A slight change in the dynamic pressure ratio results in a change of the

jet profile. Therefore, the normalized location of the beam passing through the jet was not precisely the same, which resulted in slightly different droplet diameters.

The results of the present experimental study were compared to the work of others in the literature. Although the experimental conditions and the fluid properties were different, the results of the present work fell close to those of Weiss and Worsham, Ref. (5). Also, the present results show satisfactory agreement with the predictions of Adelberg, Ref. (6). This agreement of results was once again apparent when the results were checked against those of Bitron, Ref. (17), even though his liquid jet was parallel to the airstream.

Comparison of the present results with that of Gooderum and Bushnell, Ref. (10), shows that our droplets were larger. The reasons for this disagreement are thought to be threefold. First, they injected water into flows with Mach numbers of 4.5 and 8 as compared to Mach 3 of the present study. Second, their injector had a smaller orifice diameter. Last, they investigated the injection of water into low density, low pressure flow conditions, therefore some evaporation of the spray particles could have been possible. All of these phenomenon tend to reduce the particle size compared to the present study.

This technique proved to be experimentally accurate and easily operational at our test conditions, and the data reductions were fast and easy compared to the photomicrographic technique. However, since the technique is not currently in wide use, there are no general guidelines or backlog of experience available. This increases the difficulties of adapting the technique to new experimental conditions.

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FIGURES

Figure 1: Wide-view Spark Photograph of Normal Liquid Jet Injection from a Flat Plate at M=3.0.

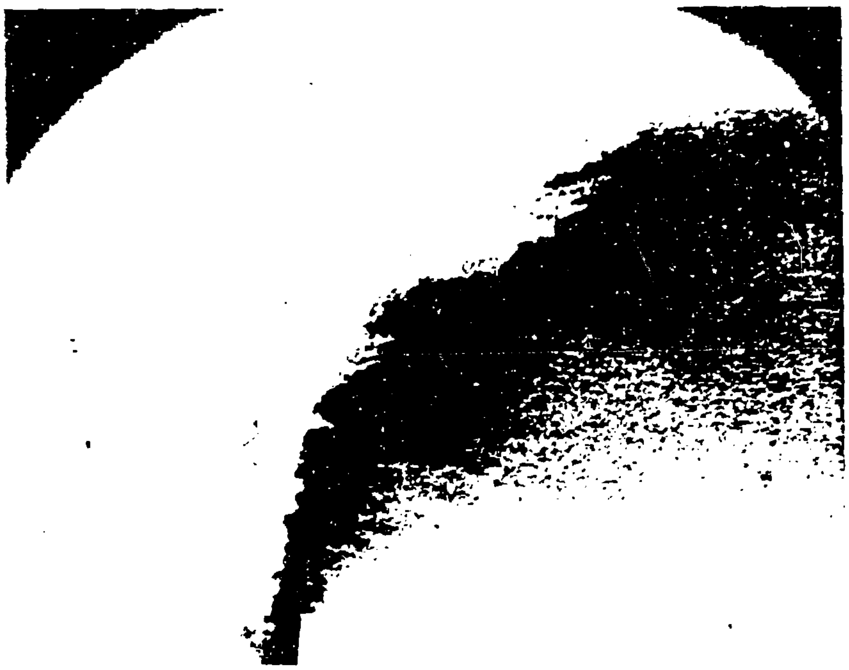

Figure 2: Close-up, Nanosecond Photograph of Normal Liquid Jet Atomization Process.

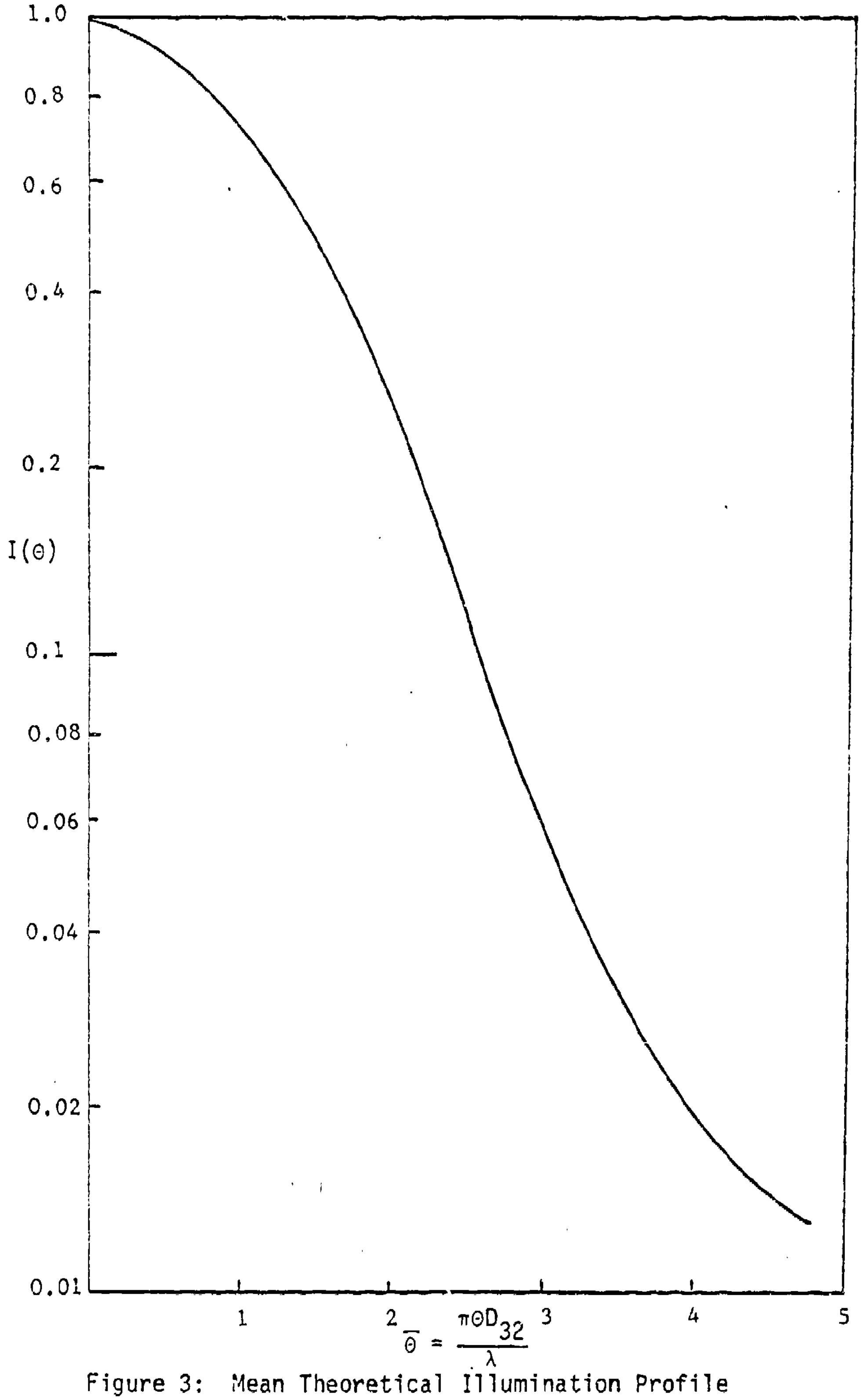

Figure 3: Mean Theoretical Illumination Profile

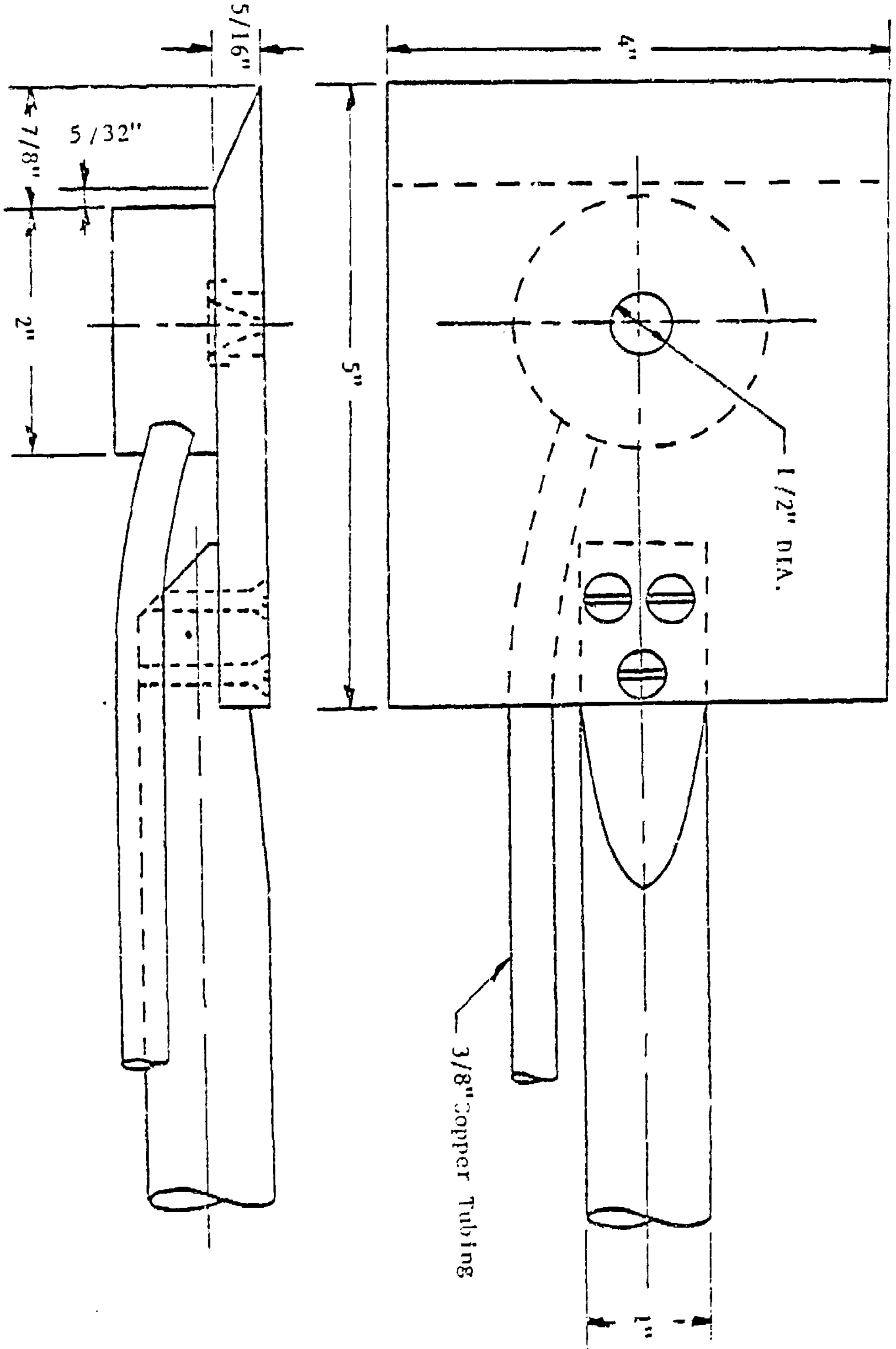

Figure 4: Flat Plate Model and Sting Mount

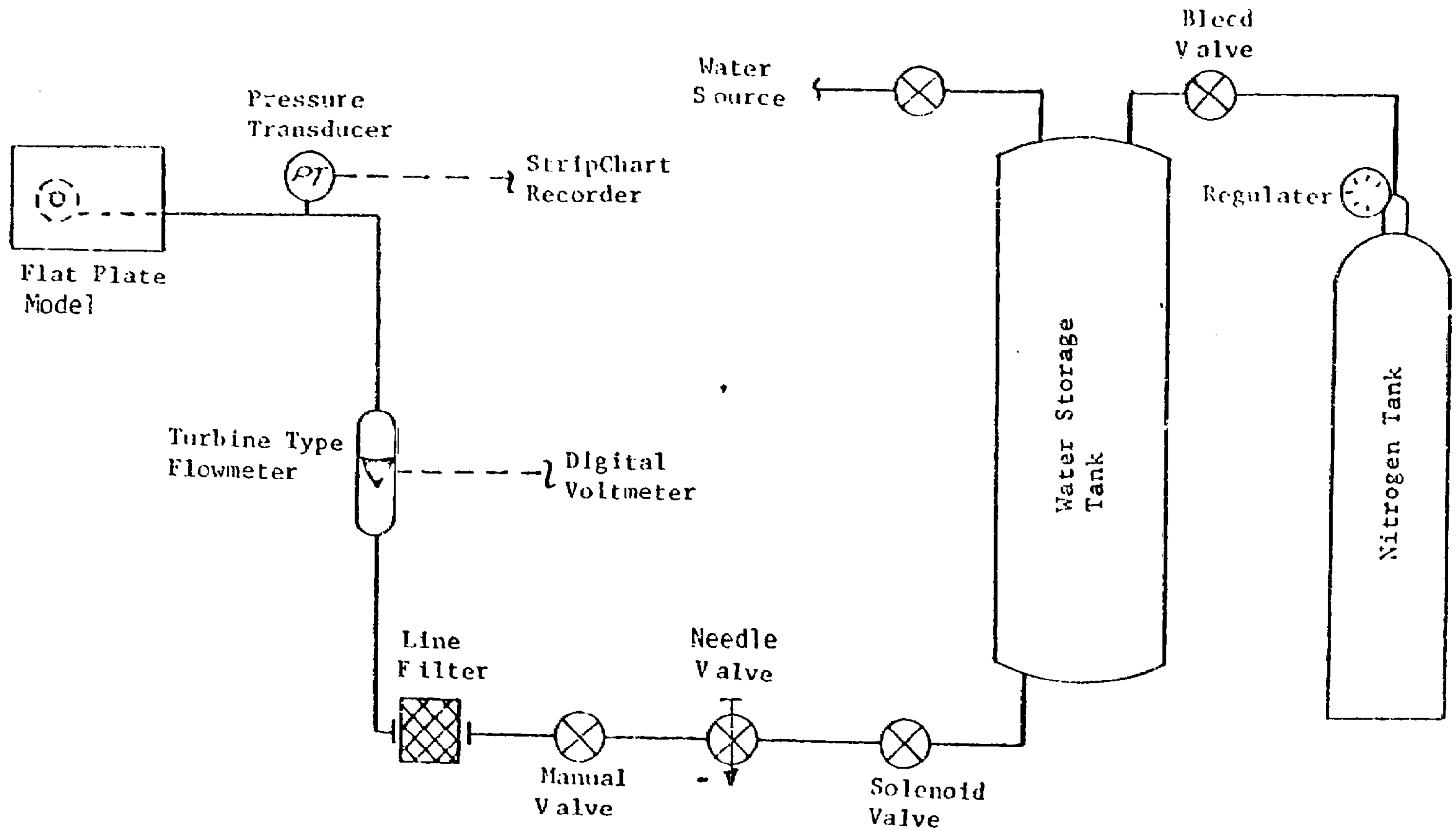

Figure 5: Schematic of the Liquid Injection System

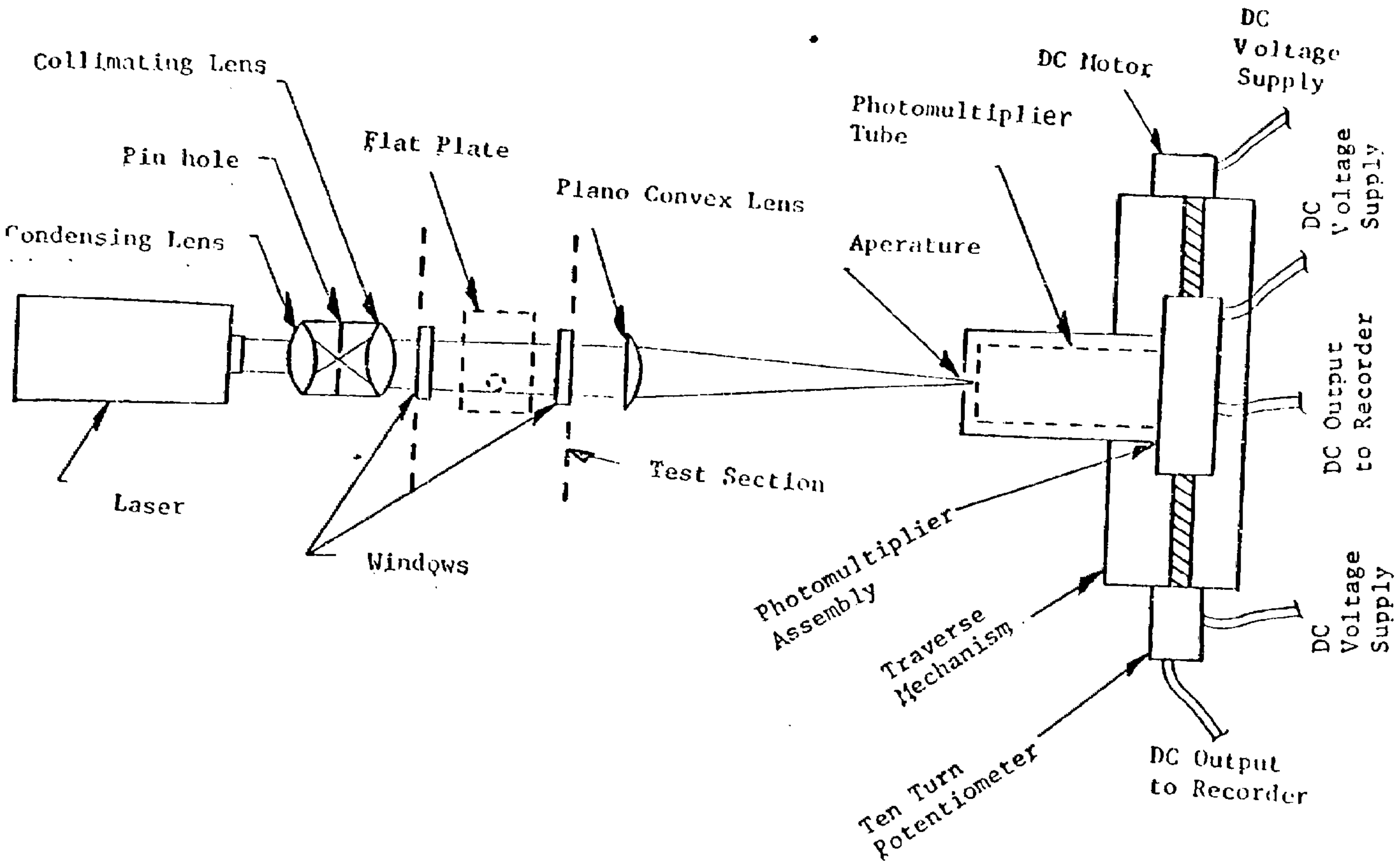

Figure 6: Schematic of the Optical Setup

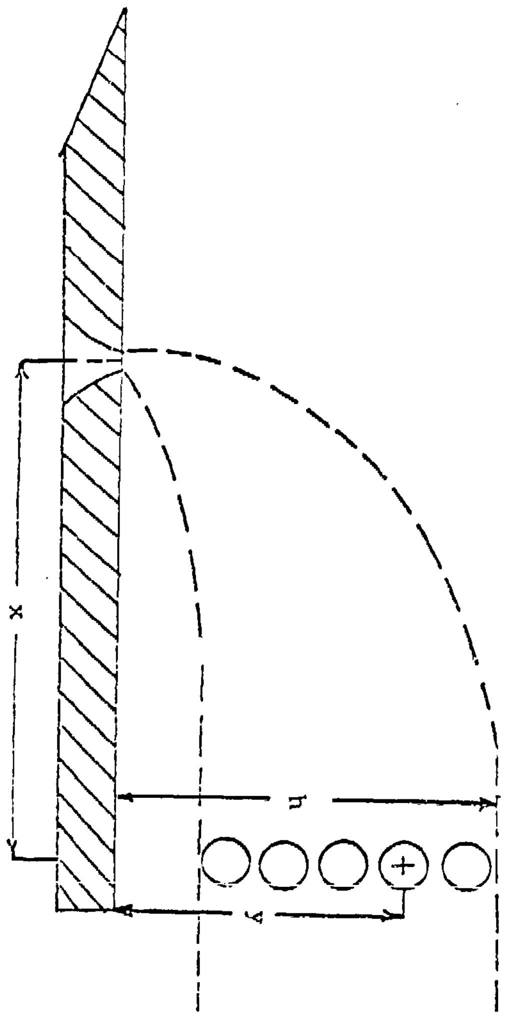

Figure 7: Schematic of Beam Location in the Spray Plume

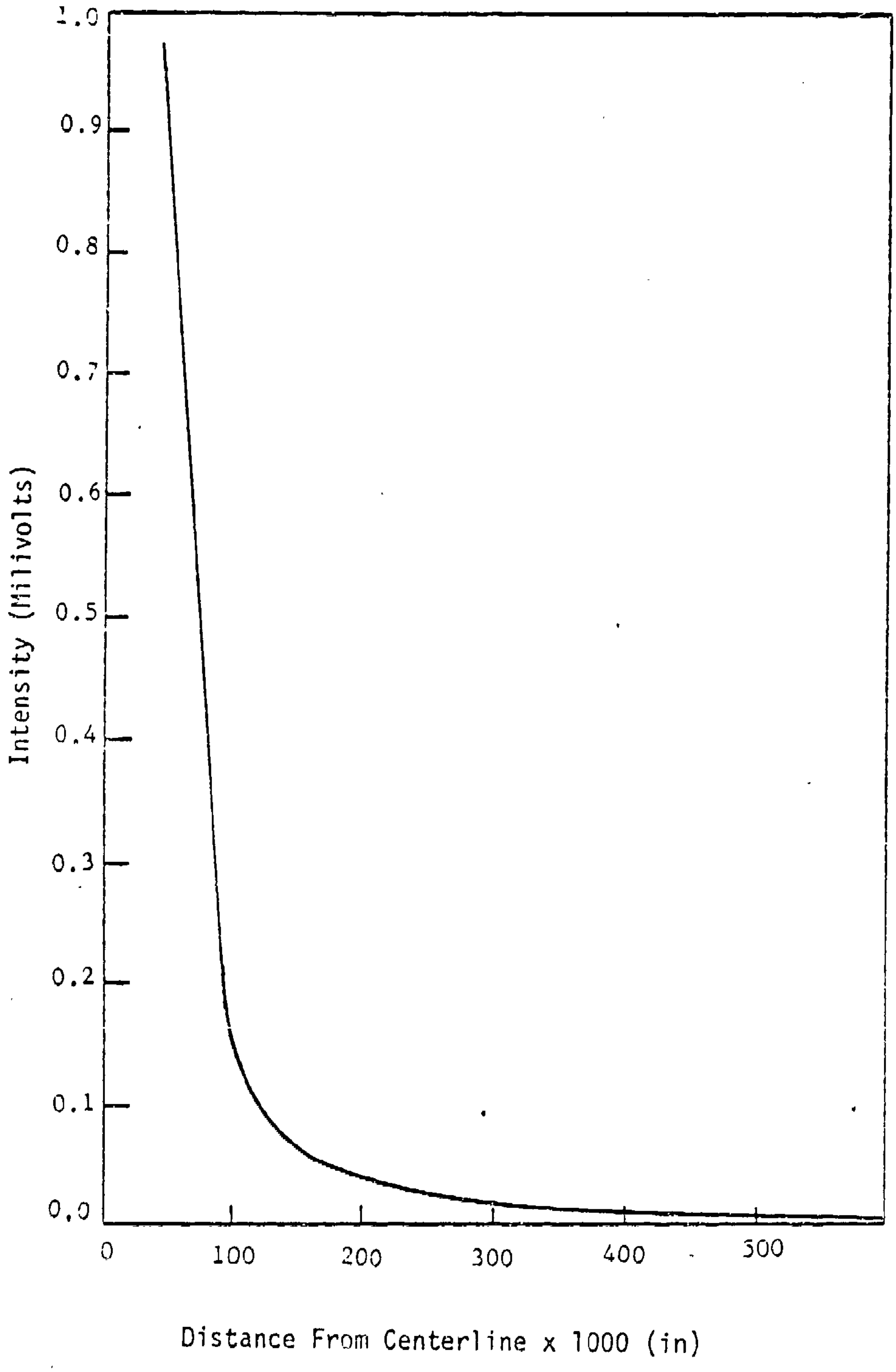

Figure 8: Zero Scattering Intensity Profile

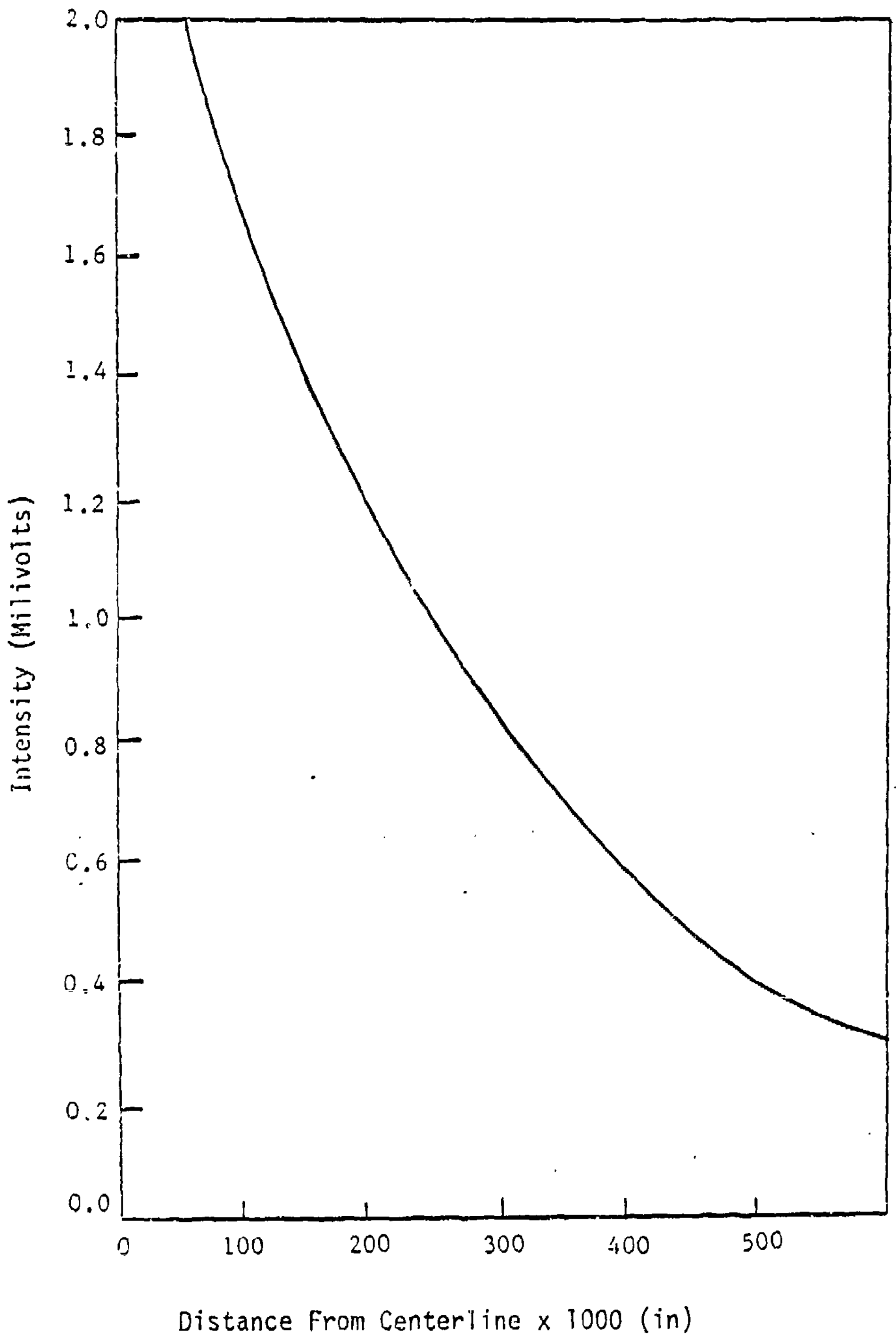

Figure 9: Scattering Intensity - Profile for a Typical Case

TABLES

Table A1 Mean Droplet Size for y/d = 15.4
and Various $\bar{q}$ and x/d

Injector Diameter = .0285 in.

Area = .000638 in.^{2}

Shape - Circular

$\frac{x}{d}$	$\frac{h}{d}$	$\frac{y}{d}$	$\bar{q}$	D_{32} Microns
48.4	14.2	15.3	6.6	20
48.4	24.2	15.3	18.0	12
48.4	30.3	15.3	27.7	13
16.6	30.3	15.3	27.7	17
48.4	40.6	15.3	49.9	12
48.4	41.2	15.3	51.3	6

Table A2 Mean Droplet Size for x/d = 82.9, y/d = 13.2 and various $\overline{q}$

Injector Diameter = .0285 in.

Area = .000638 in.^{2}

Shape - Circular

$\frac{x}{d}$	$\frac{h}{d}$	$\frac{y}{d}$	$\overline{q}$	D_{32} Microns
82.9	9.3	13.1	2.6	8
82.9	10.5	13.1	3.2	6
82.9	13.2	13.1	8.3	11
82.9	21.2	13.1	13.6	8
82.9	24.5	13.1	16.4	14
82.9	28.3	13.1	24.5	13
82.9	31.0	13.1	29.1	10

Table A3 Mean Droplet Size for $x/d = 82.9$ and $\overline{q} = 4.6$ and various y/d

Injector Diameter = .0285 in.

Area = .000638 in.^{2}

Shape - Circular

$\frac{x}{d}$	$\frac{h}{d}$	$\frac{y}{d}$	$\overline{q}$	D_{32} Microns
82.9	12.3	6.6	4.6	18
82.9	12.3	8.8	4.6	10
82.9	12.3	11.2	4.6	5
82.9	12.3	13.1	4.6	9
82.9	12.3	15.3	4.6	-

Table A3 Mean Droplet Size for x/d = 82.9 and $\overline{q}$ = 4.6 and various y/d

Injector Diameter = .0285 in.

Area = .000638 in.^{2}

Shape - Circular

$\frac{x}{d}$	$\frac{h}{d}$	$\frac{y}{d}$	$\overline{q}$	D_{32} Microns
82.9	12.3	6.6	4.6	18
82.9	12.3	8.8	4.6	10
82.9	12.3	11.2	4.6	5
82.9	12.3	13.1	4.6	9
82.9	12.3	15.3	4.6	-

Table A4 Mean Droplet Size for x/d = 82.9, $\overline{q}$ = 18.1 and various y/d

Injector Diameter = .0285 in.

Area = .000638 in.

Shape - Circular

$\frac{x}{d}$	$\frac{h}{d}$	$\frac{y}{d}$	$\overline{q}$	D_{32} Microns
82.9	24.4	6.6	18.0	17
82.9	24.4	8.8	18.0	14
82.9	24.4	17.5	18.0	12
82.9	24.4	21.9	18.0	5
82.9	24.4	26.3	18.0	4

Table A5 Mean Droplet Size for x/d = 82.9, $\overline{q}$ = 2.40 and various y/d

Injector Diameter = 0.059 in.

Area = .002732 in.^{2}

Shape - Circular

$\frac{x}{d}$	$\frac{h}{d}$	$\frac{y}{d}$	$\overline{q}$	D_{32} Microns
82.9	8.9	3.2	2.4	24
82.9	8.9	4.2	2.4	18
82.9	8.9	4.5	2.4	20
82.9	8.9	6.3	2.4	14
82.9	8.9	7.4	2.4	8
82.9	8.9	8.5	2.4	12
82.9	8.9	10.6	2.4	-

Table A6 Mean Droplet Size for x/d = 82.9,
$\overline{q}$ = 3.3 and various y/d

Injector Diameter = 0.059 in.

Area = .002732 in.^{2}

Shape - Circular

$\frac{x}{d}$	$\frac{h}{d}$	$\frac{y}{d}$	$\overline{q}$	D_{32} Microns
82.9	10.5	3.2	3.3	27
82.9	10.5	4.2	3.3	38
82.9	10.5	5.3	3.3	18
82.9	10.5	6.4	3.3	18
82.9	10.5	7.4	3.3	21
82.9	10.5	8.5	3.3	18
82.9	10.5	10.6	3.3	11
82.9	10.5	12.7	3.3	10

Table A7 Mean Droplet Size for $x/d = 82.9$, $\bar{q} = 8.2$ and various y/d

Injector Diameter = 0.059 in.

Area = .002732 in.^{2}

Shape - Circular

$\frac{x}{d}$	$\frac{h}{d}$	$\frac{y}{d}$	$\bar{q}$	D_{32} Microns
82.9	16.5	3.2	8.2	18
82.9	16.5	4.2	8.2	21
82.9	16.5	5.3	8.2	22
82.9	16.5	6.4	8.2	24
82.9	16.5	7.4	8.2	33
82.9	16.5	8.5	8.2	28
82.9	16.5	9.5	8.2	28

Table A8 Mean Droplet Size for x/d = 82.9, $\overline{q}$ = 12.5 and various y/d

Injector Diameter = 0.059 in.

Area = 0.002723 in.^{2}

$\frac{x}{d}$	$\frac{h}{d}$	$\frac{y}{d}$	$\overline{q}$	D_{32} Microns
82.9	20.4	3.2	12.5	15
82.9	20.4	4.2	12.5	18
82.9	20.4	5.3	12.5	25
82.9	20.4	6.4	12.5	19
82.9	20.4	7.4	12.5	16
82.9	20.4	8.5	12.5	19
82.9	20.4	10.6	12.5	16
82.9	20.4	12.7	12.5	15
82.9	20.4	14.8	12.5	13

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REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
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The feasibility of routine measurements of the mean droplet diameter in the spray resulting from normal injection of liquid jets into a supersonic airstream under high-density conditions in a blow-down wind tunnel employing the Diffractively Scattered Light technique was investigated in detail. Also, some studies of the effects of injector diameter, jet/free stream dynamic pressure ratios, and location in the jet plume on the mean droplet diameter were conducted. All tests were performed at M=3.0 with P_0=65 psia and $T_0 54^oR$. The important results obtained are: 1) the diffractively scattered light technique is capable of

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measuring the mean droplet diameter in the spray with good experimental accuracy if great care is exercised in the selection and use of all optical components, 2) the mean droplet size is on the order of 10 microns for injectors of the order of 0.05 in. 3) the mean droplet diameter has an inverse relation with respect to jet/free stream dynamic pressure ratio. 4) the mean droplet diameter has a direct relation with the orifice diameter. 5) the mean droplet diameter decreases as the measurement station moves farther downstream from injector orifice. 6) the mean droplet diameter variation with respect to transverse location in the spray plume does not follow a simple pattern. 7) the smallest droplets are always found near the windward edge of the spray plume.